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ETUDE DU FROTTEMENT ET DE L'USURE DE COMPOSANTS DE REACTEURS NUCLEAIRES, EN AMBIANCE D'EAU PRESSURISEE A HAUTE TEMPERATURE

FRICTION AND WEAR STUDIES OF NUCLEAR POWER PLANT COMPONENTS IN PRESSURIZED HIGH TEMPERATURE WATER ENVIRONMENTS

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SYNTHÈSE :

Dans les centrales nucléaires, de nombreux composants élancés sont soumis aux vibrations induites par les écoulements.

De plus, pour des raisons de conception et de fonctionnement, des jeux existent souvent entre ces composants et leurs supports ou leurs guides. L'interaction entre les surfaces prend la forme d'impacts ou de glissements ou d'une combinaison des deux qui produit de l'usure. Dans les générateurs de vapeur, au sommet du faisceau tubulaire, dans la zone des cintres où les vibrations sont les plus sévères, des barres anti-vibratoires de différentes conceptions sont utilisées. Ces barres sont disposées entre les rangées de tubes avec des jeux très faibles. Au début, l'usure apparaît seulement sous forme de fretting mais, avec l'augmentation des jeux, l'usure par impacts/glissements peut se produire.

La présente note fait partie d'un ensemble de publications qui rendent compte de travaux, conduits dans un cadre de partenariat pour étudier le frottement et l'usure des composants de centrales nucléaires en ambiance d'eau pressurisée à haute température. Dans ce document, les moyens d'essais à haute température et les méthodologies expérimentales sont décrits ainsi que les résultats obtenus à l'aide de deux installations très différentes (NRCC et EDF), mais pour les mêmes couples de matériaux.

En impact/glissements il apparaît des déformations plastiques en surface mais très peu de troisième corps subsiste. Des valeurs élevées des forces d'impact produisent l'apparition d'usures sévères aussi bien dans le cas des barres anti-vibratoires (BAV) en alliage 600 chromé que dans celui des BAV en acier Z6C13.

A 250 °C en eau pressurisée, l'usure des tubes en alliage 690 est supérieure quand l'antagoniste est en alliage 600 chromé que quand il est en acier Z6 C13.

En impacts/glissements la vitesse d'usure est plus importante pour les BAV que pour les tubes. En impacts obliques, les pertes de masse sur les BAV et les tubes sont voisines.

Un logiciel nouvellement développé permet d'observer les interactions tube/support et fournit des informations sur les effets instantanés et accumulés des forces de contact.

La mesure du travail d'usure tangentiel fournit un moyen de comparaison entre les résultats obtenus sur les deux machines d'usure qui produisent des mouvements différents pour le tube.

EXECUTIVE SUMMARY :

In nuclear power plants, many long slender components are subjected to high flow conditions that can induce component vibration. Furthermore, due to design and operation requirements, some kind of clearances often exists between these slender components and their supports or guides. The interaction between the two contacting surfaces can be rubbing or impacting or a combination of both resulting in wear damage. In steam generators, at the top end of the tube bundle in the U-bend region where vibration is prone to be more severe, anti-vibration bars (AVB) of various designs are used. These bars are fitted in-between tubes with near zero clearances. Initially, there may be fretting only at the interface. However, when the tubes and bars become worn, impacting and sliding could also occur in addition to fretting.

The present paper is part of a series of papers ~~that aim~~ aiming to present the friction and wear results of a collaborative study on nuclear power plant components tested in pressurized high temperature water. ~~In this paper,~~ The high temperature test facilities and the methodology in presenting the kinetics and wear results ~~will be~~ are described in detail. The results of the same material combinations obtained from two very different high temperature test facilities (NRCC and EDF) ~~will be~~ are presented and discussed.

For impact-sliding, there was evidence of surface plastic deformation but very little evidence of compacted particle layers. Higher impact loads triggered the onset of severe wear in cases with both I-600 cr and 403 s.s. AVBs.

In 250 °C pressurized water, the wear rate of I-690 tubes was higher when against the I-600 cr AVB than when against the 403 s.s. AVB. The wear rates of the AVBs were higher than those of the tubes in tests with impact-sliding motion. With oblique impacting motion, the mass losses of the tubes and the AVBs were about the same.

A newly developed software allows visual examination of the tube/support interaction and provides information on instantaneous and accumulated effects from the contact forces.

The measured tangential work provides a link for the wear results obtained from two different test rigs with different tube motions.

FRICTION AND WEAR STUDIES OF NUCLEAR POWER PLANT COMPONENTS IN PRESSURIZED HIGH TEMPERATURE WATER ENVIRONMENTS

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INTRODUCTION

In nuclear power plants, many long slender components are subjected to high flow conditions that can induce component vibration. Furthermore, due to design and operation requirements, some kind of clearances often exists between these slender components and their supports or guides. The interaction between the two contacting surfaces can be rubbing or impacting or a combination of both resulting in wear damage. In steam generators, a vibrating tube can rub and impact against the wall of the clearance hole. At the top end of the tube bundle in the U-bend region where vibration is prone to be more severe, anti-vibration bars (AVB) of various designs are used. These bars are fitted in-between tubes with near zero clearances. Initially, there may be fretting only at the interface. However, when the tubes and bars become worn, impacting and sliding could also occur in addition to fretting.

There are other components in the reactor that are subjected to similar operational and environmental conditions. For example, fretting wear could occur between the bearing pads on the fuel bundles and the pressure tubes in CANDU reactors; the control rods and their guides not only could be affected by wear damage, their friction characteristics between the sliding surfaces are of safety concerns. A coefficient of friction higher than the estimated value could cause delay in activating the control rod in cases of emergency.

Significant advances have been made in the development of techniques to alleviate flow-induced vibration in nuclear power plant components as witnessed by the wealth of information contained in a recently published ASME special booklet (1993) which contains hundreds of references in each of the topics reviewed. However, it is not possible to eliminate vibration completely and some form of component interaction, which will eventually generate wear, always exists.

Attempts to predict wear damage in steam generator tubes and other power plant components began in the early '70s. A recent review on vibration-induced wear of power plant components (Ko, 1993) was published in the special ASME booklet cited earlier. However, many of the predictive models are limited to a particular combination of test materials and are applicable only to a particular set of test conditions.

Recently, several research groups have embarked on tube wear programs that are aimed to gain better understanding of the mechanisms and mechanics involved in vibratory wear and to develop more versatile predictive wear models. For example, the tribology group at the National Research Council of Canada (NRC) has a tube wear research program supported jointly by Atomic Energy of Canada Limited and the Natural Science and Engineering Research Council of Canada (Magel et al, 1990; Iyer and Ko, 1995). The NRC tribology group is also collaborating with the tribology group at Electricité de France (EDF) and the Institut National des Sciences Appliquées de Lyon (INSA) on a parallel tube wear research project to study wear of power plant components and in particular, wear between steam generator tubes and anti-vibration bars in pressurized high temperature water (Taponat, et al, 1993, 1995). The results of several combinations of Inconel tubes vs flat anti-vibration bars of 403 s.s. and electrolytic chrome plated Inconel 600 tested under conditions of reciprocating sliding, and impacting in water have been published (Ko, et al, 1995). These results revealed that different wear mechanisms could co-exist in a wear situation. It also showed that room temperature tests can provide useful information on wear mechanisms and the wear process; for practical applications, however, tests need to be carried out in simulated operating environments.

The present paper is part of a series of papers that aim to present the friction and wear results of a collaborative study on nuclear power plant components tested in pressurized high temperature water. In this paper, the high temperature test facilities and the methodology in presenting the kinetics and wear results will be described in detail. The results of the same material combinations obtained from two very different high temperature test facilities will be presented and discussed.

EXPERIMENTAL

Test Rigs, Motion Control and Data Acquisition Systems

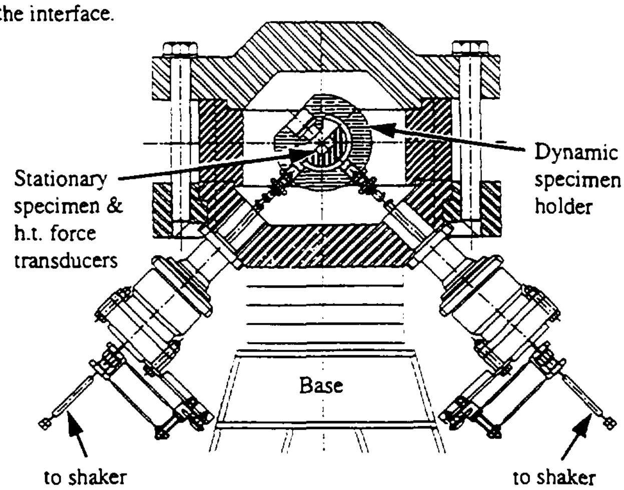
The majority of the results were obtained from tests conducted in NRC's impact/fretting (The PAGODA) high temperature test rig. Some of the results were obtained from tests conducted in EDF's high temperature tube fretting rig (The ERABLE-I) when the first and second authors were at EDF's les Renardières research establishment.

NRC high temperature Impact/Fretting Rig

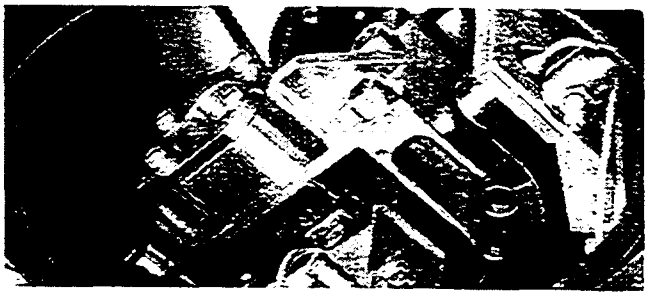
The test rig shown in Figure 1(a), consists essentially of an autoclave, two electro-magnetic shakers and the supporting structure. The tube specimen is fixed to a self-aligned holder in a ring-shaped dynamic assembly which is connected to the shakers by two flexible push rod assemblies with flexures and bellows. Due to the confined space inside the autoclave only two high temperature force transducers, mounted at 90° to each other on the plane of motion, are used. They are preloaded and anchored on the removable section of a semi-circular beam which passes through the central opening of a ring-shaped dynamic assembly and is anchored at both ends to the autoclave shell. The stationary specimen is mounted on a holder which is attached to the two force transducers. The ring-shaped dynamic assembly consists of two semi-circular halves, and the top half section can be removed for easy access to the static specimen section. The relative displacement between the dynamic and stationary specimens is monitored by an induction type high temperature proximeter probe, also attached to the semi-circular beam. Figure 1(b) shows the interior of the autoclave.

Two seal/flexure assemblies, which were designed to withstand test conditions of high temperature (270°C) and high pressure (8 MPa), are attached to the bottom section of the autoclave providing a connection between the shaker and the dynamic specimen assembly inside the autoclave. The use of a connecting rod of very small diameter at the final stage of the assembly minimises the pressure loading on the shaker which can be balanced by a d.c. offset prior to starting the test. A massive collar which slides on the exterior wall of the bottom section of the autoclave acts as a clamping anchor for the lid. All the components were made from 304 s.s.

Initially, owing to the unavailability of reliable force transducers for use in the pressurized high temperature water environment, two sets of impedance transducers, each consisting of a force transducer and an accelerometer, installed outside the autoclave on the output end of the electro-magnetic shakers were used. Unfortunately, the force signals from these two force transducers include, besides the interface contact force, also other force components that can be quite significant. These extraneous forces include the friction between the seal and the transmission rod, the inertia of the dynamic specimen assembly and the fluid it displaces, and the spring and damping forces of the shaker. A calibration procedure was carried out to evaluate these force components so that they could be removed from the overall force signals. However, as they often vary with the oscillating frequency and the operation temperature, the deduced contact forces are not always reliable. In later series of tests two high temperature force transducers will be installed immediately next to the stationary specimen to provide a direct and more precise measurement of the friction force at the interface.



(a) Cross-sectional view of the test rig



(b) Close-up view of the specimen assemblies

Fig. 1 NRC high temperature high pressure impact-fretting rig

A low-flow circulating pump is used to circulate pressurized high temperature water between the test autoclave and the pre-heater vessel. Water enters the autoclave just above the specimens helping to create a small amount of flow in that region. The outlet is located at the bottom of the autoclave and the circulating water is passed through a filter before being pumped back to the pre-heater vessel. The water temperature is regulated by temperature sensors and controllers, which also operate to prevent rapid rise in autoclave temperature. The whole system is pressurized with nitrogen gas. A pressure controller shutdowns the system if the temperature control fails and the pressure rises above the set limit. The system also incorporates a rupture disc assembly, a flow sensor and a master relief valve. Excess water due to expansion as the water temperature increases is stored in an accumulator. At the end of a test, the circulating high temperature water can be by-passed through a cooling coil to speed up the cooling process.

Motion Control and Data Acquisition Systems

The motion of the dynamic specimen is controlled by a closed-loop motion control system which provides consistency and repeatability of tests, particularly for tests with small sliding amplitudes. In the present case, the motion in the tangential direction was sinusoidal. For impact, a truncated sinusoidal normal force was applied. It was reduced to zero when the specimens were separated. The contact duration and the clearance between the samples depend on the level of the applied d.c. signal which truncated the sinusoidal signal. The sinusoidal signals were generated in a computer. They were then converted to analog signals, amplified and fed to the electromagnetic shakers. The whole system may be viewed as consisting of two subsystems: one controls the tangential movement of the dynamic specimen and the other governs the normal force. The tangential (friction) force acts as a link within the system, as it is dependent on the normal force and, in turn, influences the tangential motion.

For tests with only sliding motion, the displacement and tangential force signals were recorded in the computer at a sampling frequency of 1000 Hz. The data acquisition process was started at the same time as the normal force was applied. Later, the raw data were analyzed in the computer and the friction coefficient and tangential work were calculated for every vibration cycle. The total tangential work and the average coefficient of friction were also calculated for each test.

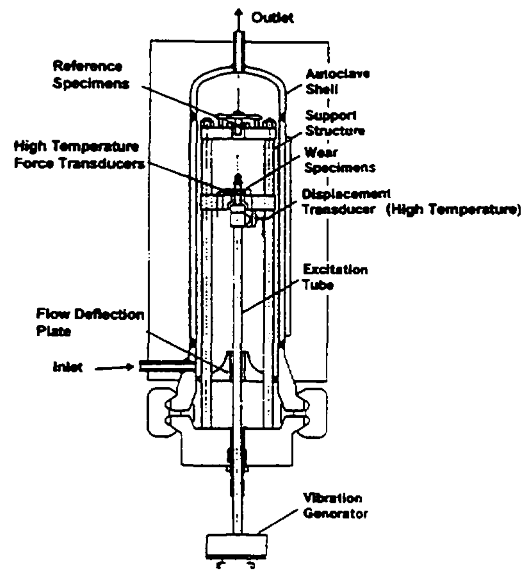
For the impact-sliding tests, signals of displacement, normal and tangential forces were recorded in "windows". In the present case, "windows" of 18 seconds at one-minute intervals were chosen. The sampling frequency was again set at 1000 Hz. The coefficient of friction, distance slid and tangential work for each vibration cycle within the "windows" were calculated. These data were then extrapolated for the duration of the interval. As in the previous case, the total tangential work and the average coefficient of friction were calculated for each test.

EDF high temperature impact/fretting rig

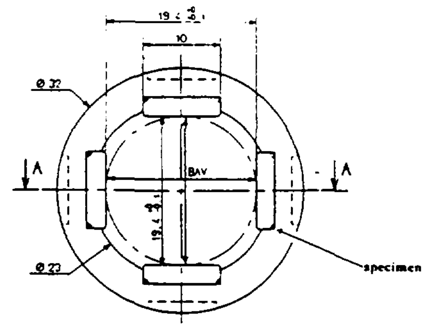
The ERABLE-I shown in Figure 2 was designed and built by the Atomic Energy of Canada Limited (AECL) in Chalk River. It consists of an autoclave in which is housed the support specimen platform and a cantilevered tube. A tube specimen is attached to one end of the cantilevered tube which passes through a seal assembly to the outside of the autoclave. The tube-support specimen holder is held by four high temperature force transducers attached to the instrument platform. For the present series of tests, four AVB specimens aligned at 90° intervals were spot-welded to the inside of a circular specimen holder. A newly designed AVB specimen holder which allows the specimens to be freely removed after tests will be used for later tests. Attached to this platform are also two high temperature displacement transducers. The instrument platform is clamped to four columns whose ends are fixed to the massive bottom section of the autoclave.

Motion is generated by a vibration generator consisting of two stepper motors connected in parallel and driven synchronously in opposite directions. Each motor turns an eccentric mass. By choosing suitable out-of-balance masses, predetermined excitation forces can be obtained and the tube can be forced to oscillate with pure impact or various orbital motions. The vibration generator is attached to the protruded end of the cantilevered tube assembly, and the excitation motion is transmitted from outside the autoclave through a flexible sleeve in the seal assembly to the tube specimen.

The ERABLE test rig is connected to a pressurized high temperature water loop which is capable of providing thermodynamic and chemical conditions close to the real operating conditions. A more detailed description of the test loop, PRESTEAU, may be found in another paper (Zbinden and Durbec, 1996).



(a) A schematic of the test rig



(b) Specimen holder for the AVB specimens

Fig. 2 EDF high temperature high pressure tube fretting rig

Data Acquisition Systems

Data acquisition for the ERABLE-1 is done by a Nicolet-Multipro system run by a micro-computer that also analyses the data and provides summarized data sheets. Analog data are recorded simultaneously by a TEAC XR7000 on videotapes as backups.

Displacement and force signals are recorded in 'windows' of 6.4s each every two hours. The acquired data are computed to calculate wear power and wear work values. At the end of each test, the results are averaged, summarized and printed.

Two different criteria were used for the data analysis; with or without contact. The 'without contact' criterion uses all recorded data for the analytical calculations. The 'contact' criterion applies an arbitrary low force value below which the signals are considered as extraneous noises and are rejected. The results of a statistical analysis for both cases are also presented in a summary sheet printed out at the end of each test. Included in this summary are also graphs of the wear power evolution during a test and graphs of the trajectories described by the centre of the dynamic specimen.

Specimen Cleaning and Weighing Procedures

The mass loss of a specimen was obtained by weighing it before and after a test on an analytical balance with an accuracy in the order of 10 μg. Prior to each weighing the specimen was cleaned with ethanol in an ultrasonic bath, dried with compressed air and then placed in a dessicator for several hours. In the case of chrome plated AVB specimens, they were dried in a furnace at 100°C for an hour before being put in the dessicator to make sure that any ethanol residue, which might have been trapped in the fissures and cavities, had completely evaporated. To avoid errors that may have arisen due to changes in humidity and temperature, two reference specimens were also placed in the dessicator with the test specimen and all three specimens were weighed. All the components of the specimen holders were also cleaned with ethanol in the ultrasonic bath after each test.

Visual display of the displacement and force signals

A software program has been developed to display the kinetics of the dynamic specimens (the tube in the present studies). The data files obtained earlier from the data acquisition system could be viewed with reduced speed and analysed using this visual display software. Thus the interaction between the dynamic and the stationary specimens can be visually examined for any chosen intervals. The results can reveal the contact forces, the stationary contact time and the actual sliding distance during a contact. Fig. 3 shows an example of a steam generator tube interacting with four AVB specimens from one of the ERABLE-1 tests. It shows approximately three cycles of motion. The number of force vectors per impact, which were superimposed on the trajectory of the dynamic specimen, provides an estimate of the time and distance of contact. For example, as the sampling rate was 20,000 Hz and the tests were run at approximately 20 Hz, there would be approximately 1000 sampling points per cycle and the duration of each force vector would represent about 50 μs.

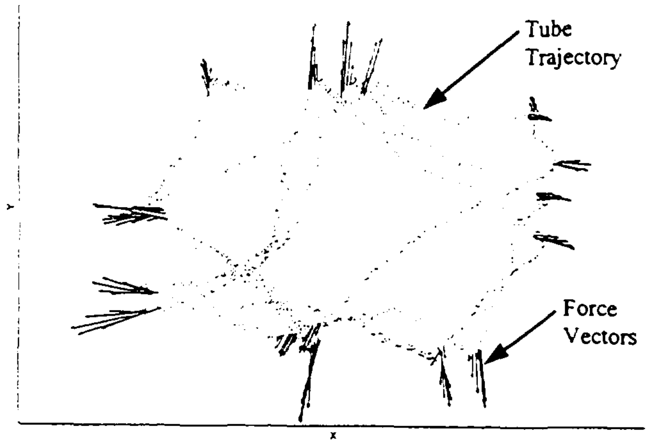


Fig. 3 Example of a computer plot showing the tube trajectory and the superimposed force vectors

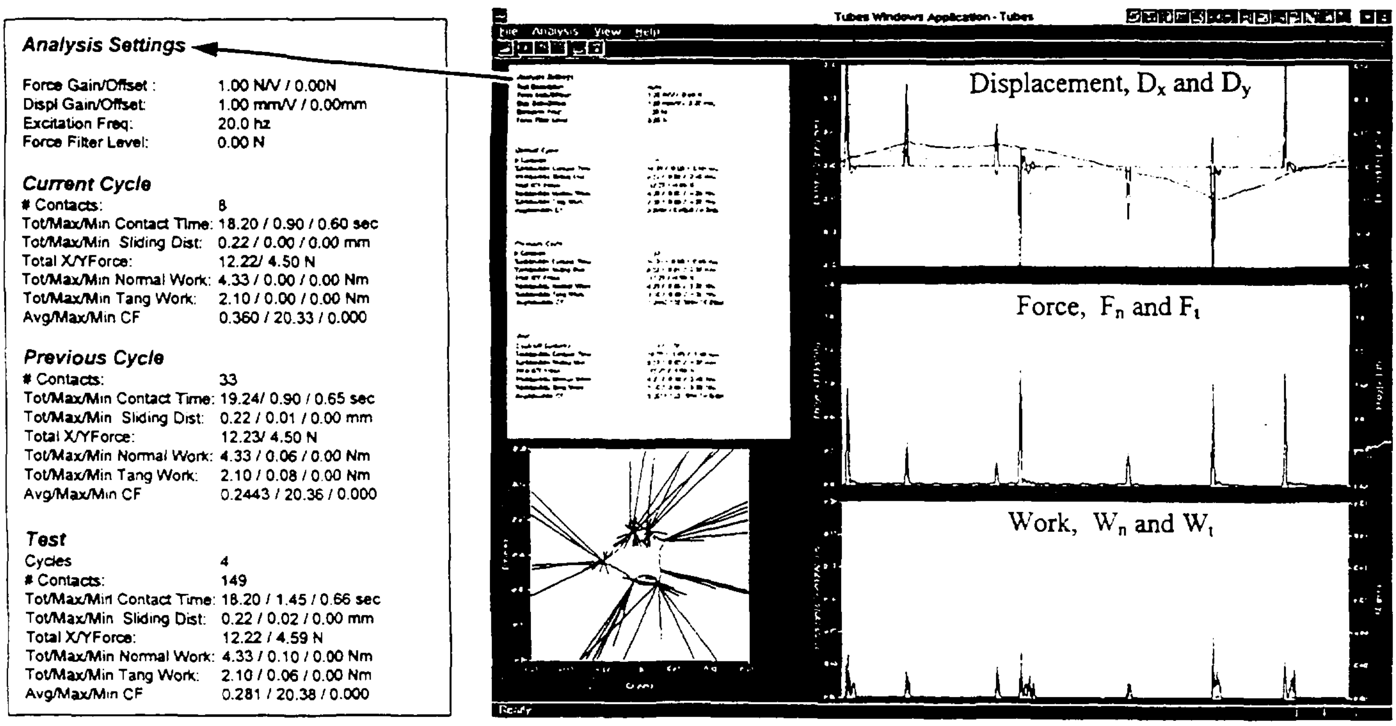


Fig. 4 A Typical Computer Output Sheet

The information on Fig. 3 reveals that, on average, there are about 6 force vectors per contact, thus the average time per contact would be around 0.3 ms which is in agreement with the results from the data analysis package used in EDF. The trajectory also showed that while some contacts had clear tangential movement, i.e., the position of the force vector shifted tangentially, others were momentarily stationary indicating that either the contact was pure impact or that the tangential component was too small to overcome the contact friction to cause a tangential movement. This kind of information is crucial in correlating the wear loss with the interaction dynamics. The program also stores and processes all the signals to provide instantaneous as well as accumulated friction force, tangential work, sliding distance and contact time at any instance up to the end of the test. The force results when continuously superimposed onto the trajectory diagram can reveal the areas that are most affected, i.e., an area subjected to repeated contacts with large accumulated tangential force. Figure 4 shows an example of an output sheet that displays the force and displacement signals for approximately one cycle. The data record presents the values of the present cycle, the previous cycle and the accumulated.

RESULTS

NRC test series

A series of tests was run for the combination I-690 tube vs. 403 s.s. AVB at various sliding and impacting frequencies. In addition, three other combinations: I-690 tube vs. I-600 cr AVB, I-600 tube vs. 403 s.s. AVB and I-600 ntt tube vs. 403 s.s. AVB were also tested for conditions of pure sliding, and combined sliding (at 20 Hz) and impacting (at 10 Hz) with a clearance of 0.15 mm between the tube and the bar. All the tests were run for 135 minutes in water at 250°C and 5.5 MPa. The results are given in Table 1. As indicated earlier in the Experimental section, even though the feedback control system could provide fairly accurate control of the sliding amplitude at 2 mm peak-to-peak, it was not possible to control the static and dynamic normal forces with accuracy for the autoclave was not equipped with high temperature force transducers when these tests were carried out. There is, therefore, an element of uncertainty in this set of data.

The results in Figures 5 and 6 show that, independent of the AVB materials, the mass loss of the AVB was substantially higher, 3 to nearly 30 times, than the mass loss of the tube. Separately, the I-690 tube sustained slightly higher mass losses, about 50% on average, when it was against I-600 cr AVB than when against 403 s.s. AVB.

EDF test series

Four 100 hour tests, two for the combination I-690 tube vs 403 s.s. AVB and two for the combination I-690 tube vs I600 cr. AVB, were tested in ERABLE-I. They were all subjected to the same environment and excitation conditions, that is, in water at 250°C and 72 bars with pH 8.8 to 9.2. The excitation frequency was 22 Hz with an elliptical orbital tube motion that has a ratio of 1.4 for the major and minor axes.

The results given in Table 2 show that the test rig, ERABLE-I, is capable of generating excellent reproducible results; for each combination the test was repeated once and the difference in mass loss was less than 5% in each case. More specifically, the results show that the mass loss of the tube was about 25% higher when it was against the I-600 cr AVB than against the 403 s.s. AVB. This trend is in agreement with that from the NRC test results. On the other hand, due to the configuration and the relatively heavy bulk mass of the EDF AVB specimen assembly, which required the four AVB specimens to be spot-welded to the assembly, it was not possible to determine accurately the mass loss of the AVB specimens. Instead, the AVB specimens were subsequently cut from the assembly and a volume measurement on each wear scar was carried out. The equivalent mass losses calculated from the volume measurements were then given in Table 2. The large difference in mass losses between the two repeated tests with I-600 cr AVB may have been the result of handling during welding and cutting. Overall, they show that unlike the results from the NRC tests, mass losses of the tube and the AVB are about the same.

Table 1 Mass loss of NRC tests
in water at 250°C and 65 bars for 135 minutes

Materials Tube/AVB	Type of test	Mass loss, mg Tube	AVB
I-690/403 s.s.	sliding only, 20Hz	0.09	0.84
	sliding, 20Hz; impact, 5Hz	0.04	0.15
	sliding, 20Hz; impact, 10Hz	0.31	1.15
	sliding, 20Hz; impact, 20Hz	0.17	1.00
	sliding, 10Hz; impact, 20Hz	*0.21*	*0.36*
	sliding, 5Hz; impact, 20Hz	*0.01*	*0.28*
I-690/I-600cr	sliding only, 20 Hz	0.15	1.03
	sliding, 20Hz; impact, 10Hz	0.74	1.78
I-600/403 s.s.	sliding only, 20Hz	0.02	0.51
	sliding, 20Hz; impact, 10Hz	0.48	1.6
I-600ntt/403 s.s.	sliding only, 20Hz	0.09	0.6
	sliding, 20Hz; impact, 10Hz	0.4	1.2

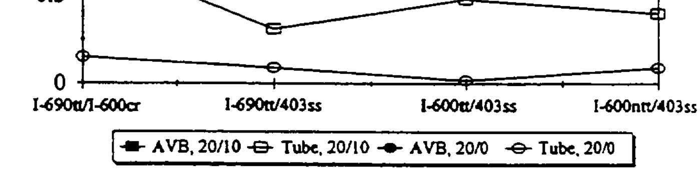


Fig. 5 Comparison of mass losses of four combinations

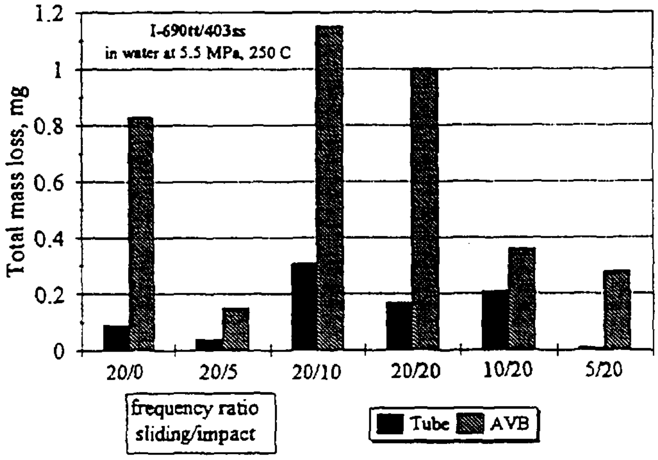


Fig. 6 Comparison of mass losses for different combined impact-sliding motions

Metallography

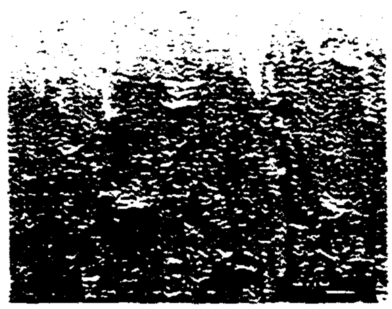
Figure 7 shows three sets of photomicrographs which illustrate significant differences in surface degradation modes. In the case of combined impact and sliding, the worn areas of the I-690/403 s.s. AVB pair, Figures 7 (a) and (b), show evidence of severe plastic deformation and surface delamination, particularly on the 403 s.s. AVB. and delamination. The worn area on the tube suface reveals patches of hard packed particle layers due to the impact-sliding motion. The worn area on the I-600cr AVB of the I-690/I600cr pair,

Table 2 Mass loss of EDF tests
in pH 9 water with chemistry control for oxygen,
at 250°C, 72 bars and flow rate 0.5 kg/s for 200 h.

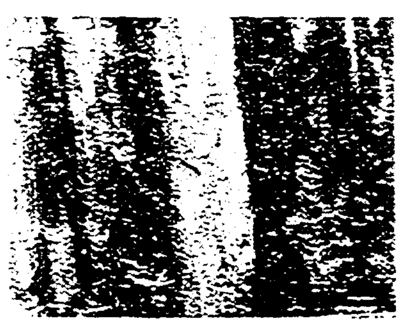
Materials Tube/AVB	Type of test	Mass loss, mg tube	AVB	work, N-m
		from wear volume		
I-690/403 s.s.	elliptical orbital motion	1.24	1.02	2210
		1.30	1.39	2810
I-690/I-600 cr.	elliptical orbital motion	1.61	1.61	4110
		1.59	0.35	2250

Fig. 7(d), shows evidence of abrasion from impact-sliding with narrow grooves. The corresponding I-690 tube is covered with particle layers, Fig. 7(c), that were formed from wear debris generated from the tube and the AVB. These layers provided certain protection for the tube, however, the impact motion, while helped to compact the particles layers, also hastened the breaking-up of these layers exposing the tube surface and resulting in further wear. In the case of sliding only, the fine abrasion and plastic deformation mechanisms produced a very smooth surface in part of the worn areas of the I-600cr AVB, Fig. 7(e). On the other hand, the 403 s.s. AVB showed much delamination, Fig. 7(f). The particle layers on the tubes, being less prone to be breaking-up due to the absence of impact, would provide a more enduable protection to the tube surface with lower mass loss.

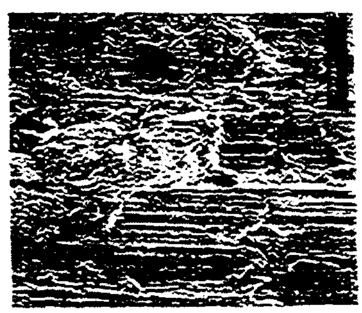
In the case of oblique impacting, such as those tests conducted in ERABLE-I, in addition to the usual appearance of delamination as shown in Fig. 7, there is also an unusual type of appearance on some parts of the wear scar of the combination with 403 s.s. AVB. They



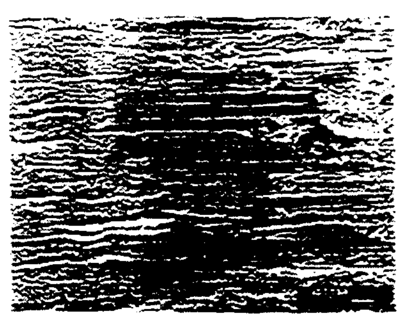
(a) I-690 tube



(b) 403 AVB
sliding, 20 Hz; impact, 10 Hz



(c) I-690 tube

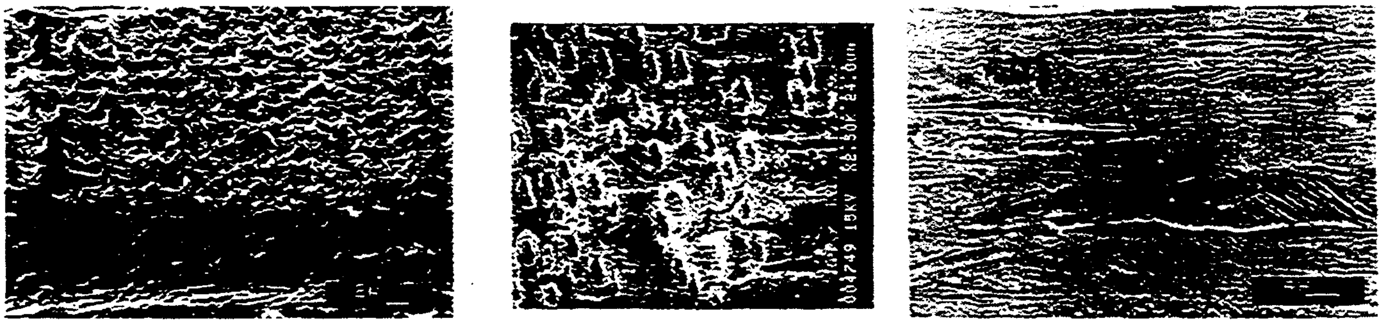


(d) I-600cr AVB
Sliding, 20 Hz; impact, 10 Hz

(e) I-600cr. AVB

(f) 403 s.s. AVB
sliding, 20 Hz

Fig. 7 Photomicrographs of worn areas showing various types of damage



(a) Scaled appearance, EDF tests-random impact *(b) Honey comb, EDF tests, random-impact* *(c) Shell appearance, NRC tests-sliding/impact*

Fig. 8 Photomicrographs of some special features in the worn areas of 403 s.s. AVB

resemble fish scales in certain areas, Figure 8(a), and a honey comb in others, Figure 8(b). Another unusual appearance of wear scars has also been observed in impact-sliding tests in room temperature water (Ko, 1995) (Fig. 8c). It is interesting to note that all these occur with tests in water subjected to either oblique impacting or a combined impact-sliding motion. Indeed, earlier tests in room temperature water with a tube-fretting rig also revealed oval shaped indentation marks in the worn area of 410 s.s. support specimens (Ko et al, 1995, Fig. 21c; Ko and Magel, 1989, Fig.8a). It was attributed to the combined effect of squeeze film, erosion and impact due to the trapped wear particles in the tube/support gap. During the course of metallurgraphic examination of steam generator tubes and control rods removed from pressurized water reactors, the first author has observed similar fish scale patterned erosion marks on some worn areas.

DISCUSSION

Orbital tube motion

The EDF test rig, ERABLE-I, can generate various orbital motions. Owing to the configuration of the tube and support arrangement, each contact between the tube and the support has a short duration and a very small sliding distance. which is a function of the clearance and the angle of impact, usually of a few µm. The actual work due to the tangential component of the impact is quite small, thus, despite a test duration nearly 100 times longer, the mass loss of the EDF tests are, on average, only about three times higher than the mass loss of the NRC tests (Tables 1 and 2). Further more, the trajectory of the dynamic tube specimen is governed by the excitation force, which is a sine function, at the instant of contact and the friction between the contact interface, which affects the exit angle of the tube at the end of contact. Consequently, the tube specimen does not always impact at the same location. Rather, it more or less precesses or skips and bounces, as illustrated in the diagrams of Figures 3 and 4, depending on the configuration of the support and the type of orbital motion. Under these circumstances, it may take longer (more contact cycles) to accumulate on one location sufficient plastic deformation that would cause surface fracture and severe wear. The orbital motion used in this series of tests provides a closer simulation of the realistic tube/support interaction. On the other hand, it has less control of the wear parameters to be investigated and takes longer to run to gain measurable mass losses.

Controlled Impact-Sliding

Two distinctive characteristics were observed with impact sliding. The first is the appearance of surface plastic deformation, particularly on the softer of the two components, and the second is the lack of evidence of compacted particle layers due to frequent separation of the two surfaces. At moderate impact loading, such as 10 N, the effect of impact does not seem to be significant. The periodic separation of the contact surfaces promotes expulsion of wear particles. At high normal loads, however, repeated impact caused accumulation of plastic deformation, as shown in Figure 7(b). Impact could also trigger the onset of severe wear. In all the severe wear cases, the chrome coating on the I-600 cr. AVB was penetrated, exposing the I-600 base material. Under these circumstances, wear was really between similar materials and the damage was severe. In the severe wear cases, there was also evidence of material transfer from the 403 s.s. bar to the tube. In some cases, impact could result in work hardening of the surface layer, altering the subsequent wear mechanism.

The majority of tests completed in the NRC impact-sliding test rig were with 403 s.s. for the AVB specimen, only a small number of tests were completed with I-600 cr. Significant differences in mass losses were observed when comparing these results with those obtained previously in room temperature water (Ko et al, 1995). Some of these room temperature results are shown in Table 3. It should be noted that the tube specimens used for these room temperature tests were I-600 instead of I-690 as it was the case for the majority of tests at high temperature. For the combinations with 403 s.s. AVB specimens, the mass losses of the tubes were about the same under both conditions. However, the mass losses of the AVB were very different; from very low at room temperature, about one fifth to one tenth that of the tube mass losses, to becoming very high in high temperature water, about 3 to 10 times that of the corresponding tube mass losses. For the combinations with I-600cr AVB specimens, the mass losses of the tubes were several times less than the AVB's in both cases. Specifically, the mass losses increased substantially at high temperature for both the tube and the AVB; 50% to 10 times higher for the tubes, and 3 to 10 times higher for the AVB. The only exception is when both the tube and the AVB sustained equally high mass losses in the severe wear case, when the static normal load was set at over 40 N and the chrome coating has been worn through. Overall, the combined mass losses of tube and AVB in high temperature water were 3 to 5 times higher than corresponding mass losses in room temperature water. The data also show that, contrary to the room temperature results, the wear rate of I-690 tube is higher when against the I-600 cr AVB than when against the 403 s.s. AVB.

There are not sufficient test data to provide a reliable assessment on the effect of impact frequency on wear. Nevertheless, there is sufficient evidence to show that the mass losses of both tube and AVB were higher for the cases with combined sliding (20 Hz) and impacting (10 Hz) than the cases with sliding (20 Hz) only. It should be noted that the tests at 5 and 10 Hz sliding would have accumulated respectively only one-quarter and one-half of the sliding cycles, as compared to the other tests at 20 Hz sliding, as all tests were run for the same duration. Therefore, the lower mass losses from these tests, as shown in Figure 6 and in italic fonts in Tables 1 and 3, reflect primarily the difference in accumulated test cycles.

With this series of tests, the motion of the dynamic specimen is controlled and monitored. The trajectory of the specimen follows a predetermined routine and the contact remains in the same general area. The sliding distance is relatively much larger, in the range of one to two mm. This type of test is more suitable for studying the effects of various wear parameters and the wear processes. The tests also take less time to run, hence are more economical.

Table 3 Mass loss at room temperature water
NRC impact-sliding tests, 135 minutes (Ko, et al, 1995)

Materials Tube/AVB	Type of test	Mass loss, mg Tube	AVB
I-600/403 s.s.	sliding only, 20 Hz	0.33	0.03
	sliding, 20 Hz; impact, 5 Hz	0.24	0.12
	sliding, 20 Hz; impact, 10 Hz	0.31	0.09
	sliding, 5 Hz; impact, 20 Hz	*0.095*	*0.055*
I-600/I600cr	sliding only, 20 Hz	0.1	0.33
	sliding, 20 Hz; impact, 5 Hz	0.02	0.33
	sliding, 20 Hz; impact, 10 Hz	0.06	0.15
	sliding, 5 Hz; impact, 20 Hz	*0.02*	*0.06*

General Discussion

It is the aim of this collaborative study to combine the knowledge gained from each series of tests together with information received from field operation to develop a more reliable predictive wear model. Although, in the present series of tests, the actual tangential work at the interface is not available due to the fact that there were no high temperature force transducers in the autoclave, an estimate could be made using the information from earlier test series carried out in room temperature water, with which a triaxial force transducer was used, as similar excitation conditions were used in both the room temperature and high temperature tests. A rough estimate gives the total tangential work for the tests with combined sliding (20Hz) and impact (10Hz) in the range of 500 Nm. A comparison of the tangential work and the mass losses from the two series of high temperature tests showed that the EDF tests were 4 to 8 times higher in tangential work and 2 to 10 times higher in mass loss than respectively those of the NRC tests. A more precise comparison can be made when the high temperature force transducers have been installed in the NRC autoclave. Nevertheless, the tangential work does provide a link for these two series of tests despite the differences in test duration and tube motion.

CONCLUSIONS

For impact-sliding, there was evidence of surface plastic deformation but very little evidence of compacted particle layers. Higher impact loads triggered the onset of severe wear in cases with both I-600 cr and 403 s.s.AVBs.

In 250°C pressurized water, the wear rate of I-690 tubes was higher when against the I-600 cr AVB than when against the 403 s.s. AVB. The wear rates of the AVBs were higher than those of the tubes in tests with impact-sliding motion. With oblique impacting motion, the mass losses of the tubes and the AVBs were about the same.

A newly developed software allows visual examination of the tube/support interaction and provides information on instantaneous and accumulated effects from the contact forces.

The measured tangential work provides a link for the wear results obtained from two different test rigs with different tube motions.

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